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A Comparison of Vibration and Oil Debris Gear Damage Detection Methods Applied to Pitting Damage

Paula J. Dempsey
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A COMPARISON OF VIBRATION AND OIL DEBRIS GEAR DAMAGE DETECTION METHODS APPLIED TO PITTING DAMAGE

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Abstract: Helicopter Health Usage Monitoring Systems (HUMS) must provide reliable, real-time performance monitoring of helicopter operating parameters to prevent damage of flight critical components. Helicopter transmission diagnostics are an important part of a helicopter HUMS. In order to improve the reliability of transmission diagnostics, many researchers propose combining two technologies, vibration and oil monitoring, using data fusion and intelligent systems. Some benefits of combining multiple sensors to make decisions include improved detection capabilities and increased probability the event is detected. However, if the sensors are inaccurate, or the features extracted from the sensors are poor predictors of transmission health, integration of these sensors will decrease the accuracy of damage prediction. For this reason, one must verify the individual integrity of vibration and oil analysis methods prior to integrating the two technologies. This research focuses on comparing the capability of two vibration algorithms, FM4 and NA4, and a commercially available on-line oil debris monitor to detect pitting damage on spur gears in the NASA Glenn Research Center Spur Gear Fatigue Test Rig. Results from this research indicate that the rate of change of debris mass measured by the oil debris monitor is comparable to the vibration algorithms in detecting gear pitting damage.

Keywords: Damage detection; Gears; Health monitoring; Oil debris monitor; Vibration

Introduction: Various techniques exist for diagnosing damage in helicopter transmissions. The method most widely used involves monitoring vibration. Algorithms have been developed using vibration data collected from gearbox accelerometers to detect when gear damage has occurred. These vibration algorithms are then used for assessing gearbox condition. Oil debris monitoring is also used to identify abnormal wear related conditions at an early stage. Oil debris monitoring for gearboxes consists mainly of off-line oil analysis, or plug type chip detectors. For off-line analysis, oil samples are collected, sent to labs and analyzed for trends that indicate component failure. A plug type chip detector uses a magnet that captures debris. The state of an indicator changes when the debris forms an electrical bridge between the contacts. Although not commonly used for gearboxes, many engines have on-line oil debris monitors that can count particles and determine the size and the accumulated mass. And new intelligent oil monitors are currently being developed that have the ability to identify major wear fault types [1].

The goal of future HUMS is to increase reliability and decrease false alarms by replacing simple one parameter limits with an integrated intelligent system. The current fault detection rate of commercially available HUMS through vibration analysis is 60 percent. False warning rates are average 1 per hundred flight hours [2]. Vibration based systems require extensive interpretation by trained diagnosticians to create algorithms that indicate impeding failures. Commercially available oil debris monitor systems require trending the data to set limits to predict damage based on the number of particles or the accumulated mass.

Integrating the sensors into one system is the critical key to improving the detection capabilities and the probability that damage is detected [3]. Comparing the performance of vibration and oil based measurement techniques is the first step required prior to fusing the methods into a reliable health monitoring system.

The objective of the work reported herein is to evaluate and compare the performance of vibration and oil debris monitoring based techniques in detecting gear pitting damage. Experimental data from controlled tests on a spur gear fatigue test rig are used to compare the relative performance of these methods.

Apparatus and Test Procedure: Experimental data was recorded from tests performed in the Spur Gear Fatigue Test Rig at NASA Glenn Research Center [4]. Figure 1 shows the test apparatus in the facility. Operating on a four square principle, the shafts are coupled together with torque applied by a hydraulic loading mechanism that twists one coupling flange with respect to the other. The power required to drive the system is only enough to overcome friction losses in the system [5]. The test gears are standard spur gears having 28 teeth, 3.50 inch pitch diameter, and .25 inch face width. The test gears are run offset to provide a narrow effective face width to maximize gear contact stress while maintaining an acceptable bending stress.

Fatigue tests were run in a manner that allows damage to be correlated to the vibration and oil debris monitor data. For these tests, run speed was 10,000 RPM and applied torque was 71 ft-lbs. Prior to collecting test data, the gears were run for 1 hour at a torque of 10 ft-lbs. Test gears were inspected periodically for damage throughout the duration of the test. When visual damage was found, the damage was documented and correlated to the test data.

Data was collected using vibration, oil debris, speed and pressure sensors installed on the test rig. Vibration was measured on the gear housing and through the shaft using miniature, lightweight, piezoelectric accelerometers. Location of both sensors is shown in Figure 2. These locations were chosen based on an analysis of optimum accelerometer locations for this test rig [6]. Oil debris data was collected using a commercially available oil debris sensor that measures the change in a magnetic field caused by passage of a metal particle where the amplitude of the sensor output signal is proportional to the particle mass. The sensor measures the number of particles, their approximate size (125 to 1000 microns) and calculates an accumulated mass [7]. Shaft speed was measured by an optical sensor that creates a pulse signal for each revolution of the shaft. Load pressure was measured using a capacitance pressure transducer.

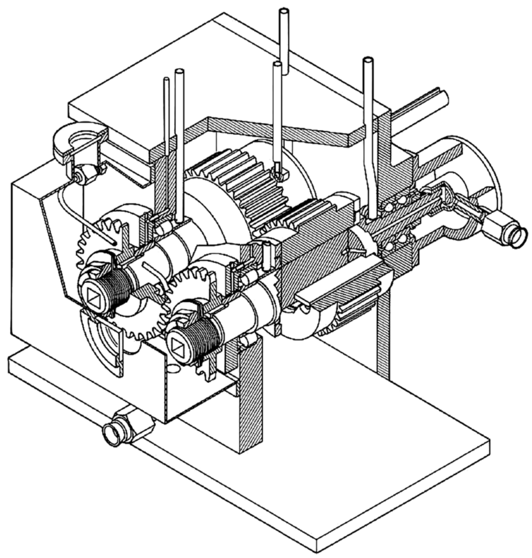


Figure 1.—Spur Gear Fatigue Test Rig.

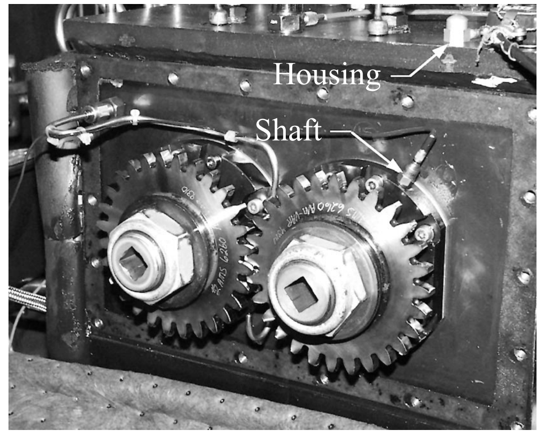


Figure 2.—Accelerometer locations on Spur Gear Fatigue Test Rig (gearbox cover removed).

Oil debris monitor, speed, pressure, and raw vibration data was collected and processed in real-time using the program ALBERT, Ames-Lewis Basic Experimentation in Real Time, co-developed by NASA Glenn and NASA Ames. Oil debris and pressure data was recorded once per minute. Vibration and speed data was sampled at 200 KHz for one-second duration every minute. Vibration algorithms FM4 and NA4 were calculated from this data and recorded every minute.

Vibration Diagnostic Parameters: Two vibration diagnostic parameters were used in this analysis, FM4 and NA4. FM4 was developed to detect changes in the vibration pattern resulting from damage on a limited number of teeth [8]. NA4 was developed to detect the onset of damage and to continue to react to the damage as it spreads [9]. FM4 and NA4 are dimensionless parameters with nominal values of approximately 3. When gear damage occurs, the value increases for both FM4 and NA4. Prior to calculating FM4 and NA4, the time synchronous average of the vibration data is calculated. Signal time synchronous averaging is a technique used to extract periodic waveforms from additive noise by averaging the vibration signal over one revolution of the shaft. The signal time synchronous average is obtained by taking the average of the signal in the time domain with each record starting at the same point in the cycle as determined by the once per rev signal. The desired signal, which is synchronous with the shaft speed, will intensify relative to the non-periodic signals. This time synchronous average signal is used as a basis for FM4 and NA4 methods.

Several statistical and filtering operations are used to calculate FM4. First the regular meshing components are filtered from the signal resulting in a difference signal. The regular meshing components are the shaft and meshing frequencies their harmonics and first order sidebands. Two statistical operations, standard deviation and kurtosis, are then performed on the filtered signal. Kurtosis is the function that quantifies how “Gaussian” a time history is, and is defined as the fourth moment of a probability density function [10]. FM4 is calculated as follows:

$$FM4 = \frac{K}{(RMSDS)^4} \tag{1}$$

where
K = kurtosis
RMSDS = standard deviation of the difference signal

Kurtosis, the fourth moment of a probability density function, is calculated by,

$$K = \left[\frac{1}{N} \sum_{i=1}^{N} \left(d_i - \bar{d} \right)^4 \right] \tag{2}$$

where
d = difference signal
$\bar{d}$ = mean value of the difference signal
N = total number of interpolated data points per reading
RMSDS, the standard deviation of the difference signal is calculated by [11]

$$RMSDS = \left[\frac{1}{N} \sum_{i=1}^{N} \left(d_i - \bar{d} \right)^2 \right]^{\frac{1}{2}} \tag{3}$$

The NA4 parameter is calculated in a similar manner to FM4, with two alterations. The first change involves retaining the first order sidebands when calculating the regular meshing components of the difference signal. The second change is that while FM4 is calculated by the kurtosis of a data record divided by the square of the variance of the same record, NA4 is divided by the square of the average variance. The average variance is the mean value of the variance of all previous data records in the run ensemble [12].

$$NA4(M) = \frac{N \sum_{i=1}^{N} \left(r_i - \bar{r} \right)^4}{\left\{ \frac{1}{M} \sum_{j=1}^{M} \left[\sum_{i=1}^{N} \left(r_{ij} - \bar{r_j} \right)^2 \right] \right\}^2} \tag{4}$$

where
r = residual signal = shaft and meshing frequencies and their harmonics removed from FFT of time synchronous averaged signal
$\bar{r}$ = mean value of residual signal
N = total number of interpolated data points per reading
i = interpolated data point number per reading
M = current reading number
j = reading number

Discussion of Results: The analysis discussed in this section is based on data collected from two gear tests that ended when pitting damage occurred. Figure 3 is a plot of the data measured during testing of Gear Set 1. Vibration algorithms FM4, NA4, and the accumulated mass measured by the oil debris monitor are plotted versus reading number. Readings were recorded once per minute. This test collected 13716 readings over 228 hours. FM4 and NA4 were calculated for both the accelerometer located on the shaft and the accelerometer located on the housing. During the 228 hours of testing, ten shutdowns occurred. To restart after shutdown, the rig was brought up to speed, then the load was reapplied. These load changes caused significant spikes in the NA4 plot that can be observed on Fig. 3 following shutdowns at readings 1455, 2576, 3663, 3736, 3982, 4128, 4681, 5035, 5309, and 5435. The sensitivity to load is due to the changes of the running average in the denominator of this algorithm. Unfortunately, this change was due to a load change, not a damaged gear. The sensitivity of NA4 to even minor changes in load has been documented in several research papers [13, 14]. Additional research is needed to correct for the sensitivity of NA4 to load. Another observation to note on Fig. 3 is that after the shutdown at reading 4681, the oil debris monitor indicated one 725 to 775 micron particle passed through the sensor, causing a large increase in the accumulated mass. This one large chip was apparently flushed out of the line when the rig was restarted after the shutdown.

Initial pitting appeared to occur at reading 11647. Initial pitting for the purpose of this paper is defined as pits less than 1/64 inches in diameter with a depth less than 1/64 inches. At the completion of the test, the gears were inspected for damage. Initial pitting was observed on tooth 12 of both the driven and driver gears. By visual observation of the overall plot on Fig. 3, all parameters showed a significant increase when pitting damage began to occur. Figure 4 has an expanded Y scale in order to observe the increase in NA4 and FM4 as pitting damage progressed. Reviewing Figs. 3 and 4, vibration algorithms FM4 and NA4 for both accelerometers, and the accumulated mass increase significantly when pitting damage occurs. Figure 5 shows a photo of the damage on the driver tooth at the completion of the test.

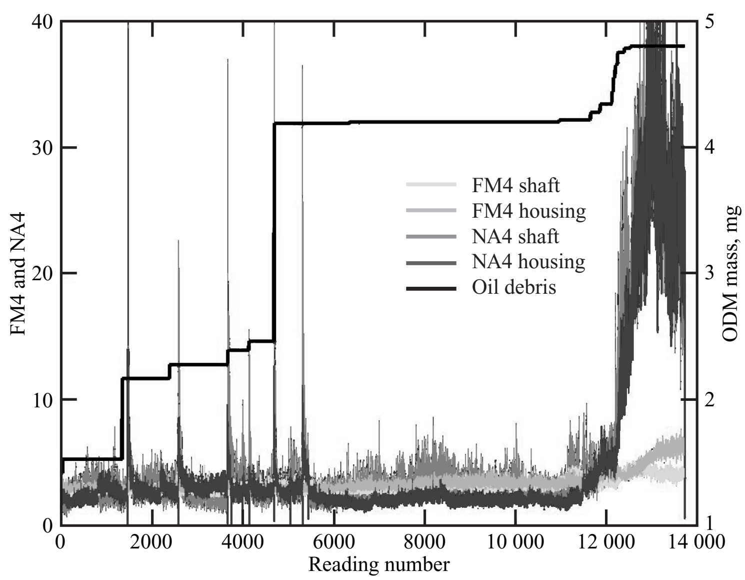


Figure 3.—Plot of vibration and oil debris monitor data for gear set 1.

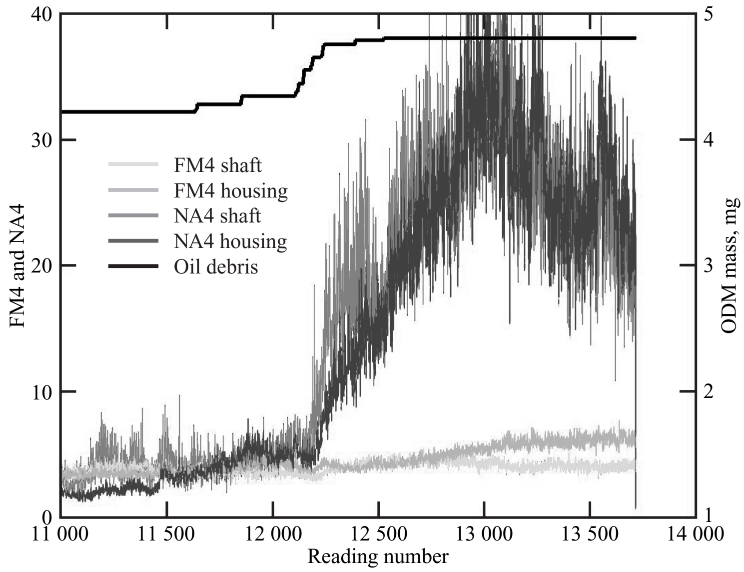


Figure 4.—Plot of vibration and oil debris monitor data for gear set 1 (expanded scale).

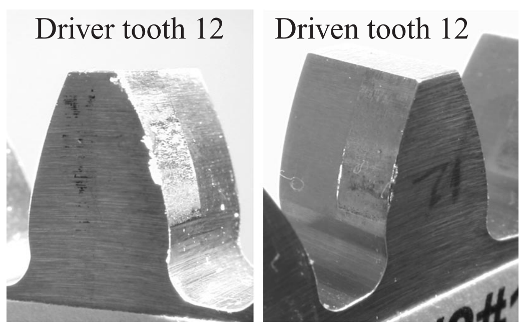


Figure 5.—Gear damage at completion of gear set 1 test.

During startup of the rig, chips generated during test setup pass through the sensor. And, as mentioned previously, these chips may become trapped in the line, then flushed through the sensor during restarts. Based on this data, and experience from gear tests where pitting occurred or did not occur, a simple threshold limit on number of particles or accumulated mass is not the best method to indicate damage. Instead, results from gear tests indicate that the step change of the mass over the time from the last step change of the mass is a better limit. An equation that describes this is shown below:

$$\frac{m_N - m_{N-1}}{t_N - t_{N-1}} \geq .005 \tag{5}$$

where
m = accumulated mass
t = time in minutes
N = reading number when step change in mass occurred

Based on experimental data collected by the oil debris monitor during this experiment and several experiments when no damage occurred, a value of .005mg/minute was calculated as the limit to indicate pitting damage has occurred for this analysis.

Defining threshold limits for vibration algorithms to indicate when pitting damage has occurred is a more challenging task. Several research papers defined 7 as threshold value to indicate pitting damage for vibration parameter NA4. For parameter FM4, values for initiation of pitting range from 3 to 5.4 [9, 15]. Three additional tests were run on the test rig, which generated no damage on the test gears. The run hours ranged from 350 to 497 hours for each test with a total of 1204 hours. The data recorded for FM4 during the tests when no damage occurred was used to set a threshold limit for this algorithm. This was done by first calculating the mean and standard deviation of FM4 during each test. Next, 3 times the standard deviation was added to the mean [16]. Since the number of readings for each test varied, a weighted average of the limit was calculated based on the number of readings recorded during each test. The weighted average was used as the threshold limit for FM4. From this exercise the limit for FM4 was set at 4.4503. Based on these threshold limits, FM4 and the oil debris monitor indicate pitting damage sooner than does NA4. NA4 had the most false alarms for this test. This was mainly due to the sensitivity of NA4 to the load changes that occurred during this test. Since several factors other than gear damage can cause vibration levels to increase, future research is required to refine vibration algorithm limits to minimize false alarms.

Figures 6 and 7 are plots of the data measured during testing of Gear Set 2. Vibration algorithms FM4, NA4, and the accumulated mass measured by the oil debris monitor are plotted versus reading number. Readings were recorded once per minute. During this test, 5314 readings were collected over 88 hours. FM4 and NA4 were calculated for both the accelerometer located on the shaft and the accelerometer located on the housing. Initial pitting appeared to occur at reading 5020. Gears were inspected at Reading 5181 and initial

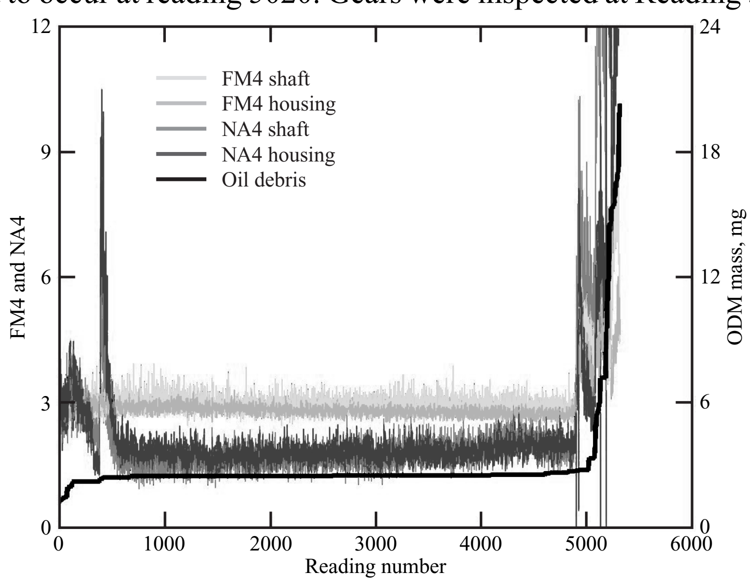


Figure 6.—Plot of vibration and oil debris monitor data for gear set 2.

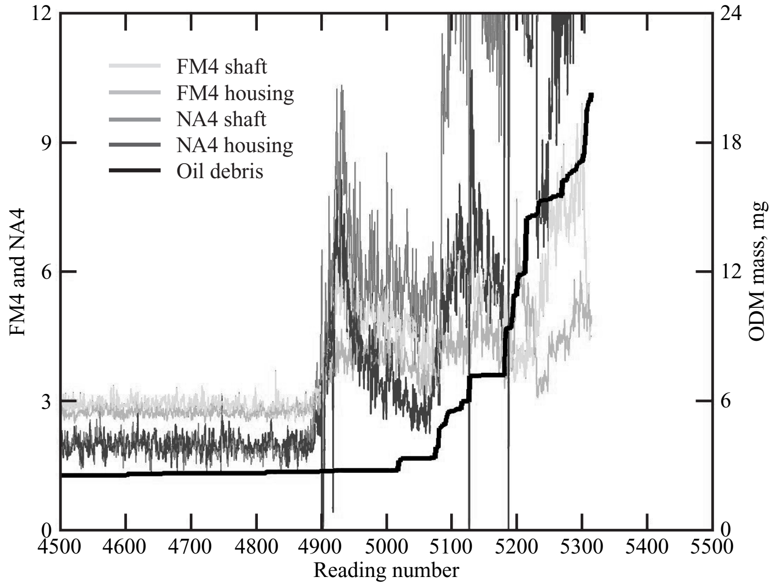
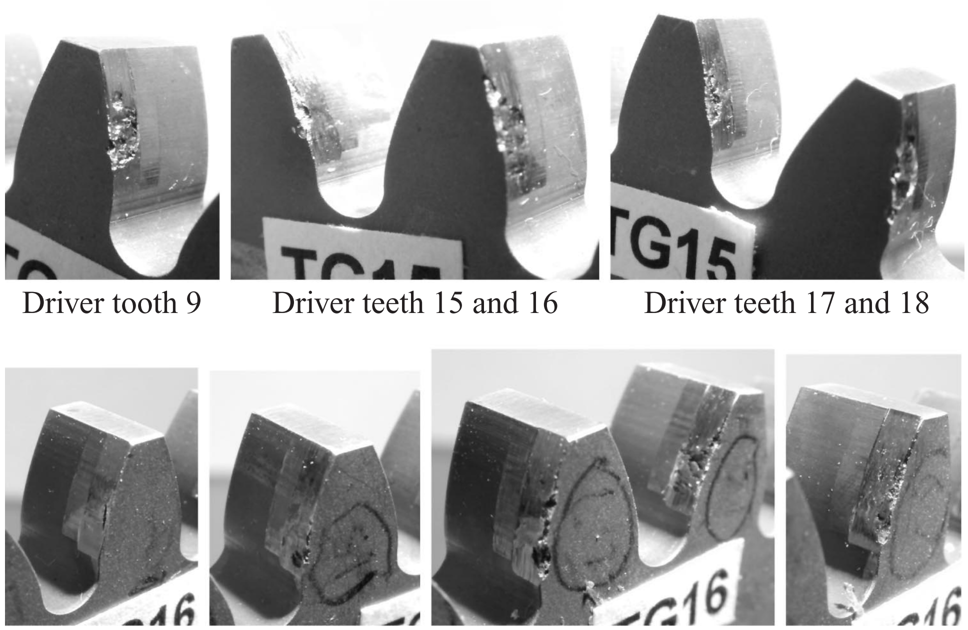


Figure 7.—Plot of vibration and oil debris monitor data for gear set 2 (expanded scale).



Driver tooth 9 Driver teeth 15 and 16 Driver teeth 17 and 18

Driven tooth 9 Driven tooth 15 Driven teeth 16 and 17 Driven tooth 18

Figure 8.—Gear damage at completion of gear set 2 test.

pitting was observed on teeth 15 and 16 of the driver gear and teeth 15, 16, and 17 of the driven gear. At the completion of the test, destructive pitting and spalling were observed on several of the teeth. Destructive pitting is more severe than initial pitting and the pits are larger in size. If the test continues, the pitting will get worse and the gear teeth may crack and break off. For the purpose of this paper, damage is defined as destructive pitting if the depth is greater than 1/64 inches and the diameter is less than 1/16 inches. Spalling is similar to destructive pitting but the pits are larger in diameter and cover a considerable area (greater than 50 percent of tooth contact area). Damage is defined as spalling if the depth is greater than 1/64 inches and the diameter is greater than 1/16 inches. The gears were inspected at the completion of the test. From the inspection, initial pitting was observed on driver teeth 19, 24, and 27, and driven tooth 14. A combination of initial and destructive pitting was observed on both the driver and driven gears teeth numbers 9, 15, 16, 17, 18, and 24. Spalling was beginning to occur on driver teeth 17 and 18. Figure 8 shows photos of the damaged teeth at test completion.

Referring to Figs. 6 and 7, all parameters show a significant increase when pitting damage occurs. A shutdown at reading 380 caused the large spike of NA4. Shutdowns also occurred at readings 4903, 4919, 5128, and 5181. As shown on Fig. 7, after the shutdown at Reading 4919, FM4 and NA4 increased then decreased slightly. This increase/decrease is most likely due to the load change. An integrated system that compensates for load changes will improve the prognostic capability of the vibration algorithms.

Conclusions: The goal of this research was to compare the capability of vibration algorithms FM4, NA4 and the oil debris monitor to detect gear pitting failure. This preliminary research assessed the reliability of the individual parameters when detecting gear pitting. Improving the reliability of the individual parameters must be done before attempting to integrate the three parameters into an intelligent health monitoring methodology that can be applied to a helicopter transmission system. Once improvements are made to the individual parameters, the parameters can be combined to improve prediction of gear failure.

Results of this research indicate that several improvements need to be made to the parameters to increase their individual performance. The first is the significant effect load changes have on NA4. This algorithm must be modified to decrease its sensitivity to load changes. Future research includes looking into a relationship between load and NA4 to improve the performance of this algorithm. The second area that needs improvement is a method to set alert and fault threshold limits for vibration algorithms. The third improvement requires the oil debris monitor to differentiate existing chips trapped in the lubrication line, that are flushed through the sensor during restarts, from chips due to actual pitting damage.

Based on the data collected, FM4, NA4, and the oil debris monitor each showed a significant increase when pitting damage began to occur. Analytical techniques must be defined to quantify damage thresholds, and to minimize the false alarms for the parameters. Once the performance of each parameter is improved, the three parameters can be combined into an intelligent system that can integrate the vibration and oil debris data, interpret the data, and make an accurate decision based on the data.

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